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# Automata Theory in the WEFW nexus: Experience from the cities in the Global South

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***Abstract*— *The major societal interests among the urban community at the moment represent a wide array of sustainable energy, climatic regulation, proper water use and sustainable production and consumption of renewable resources. As people migrate to urban areas, and more than half of the world population now live in cities, more pressure is put on the Water-Energy-Food-Waste (WEFW) systems. Devoid of plans for sustainable provision of WEFW services, cities may suffer water stress, starvation, load shedding and choked with waste. In this regard, among the dilemmas faced by urban managers is which methodologies would appropriately fix these problems and why. They can either (i) treat each of these problems individually or (ii) address them as one complex problem. This paper adopts the Automata Theory (AT) to explain how these options are affected by the nature of WEFW nexus, in what way the effects are transferred in the states and the opportunities and cautions from this nexus that affect the management of urban dynamics. A total of 16 articles analysing WEFW nexus and 20 articles covering interactions between WEFW elements were reviewed. Results show that the management of the interconnections between the WEFW elements contributes to either the realization or the breakdown of the urban systems. Empirical studies to establish resultant interactions between nexus sub-systems and developing integrated planning tools for inclusive policy processes that consider the vast array of this nexus in the current complex systems is fundamental.*

***Keywords*— *Water-Energy-Food-Waste nexus, Automata.***

## I. INTRODUCTION

Currently, Asia and Africa still have a predominantly rural-to-urban population compared to Europe, North America and Oceania (Wiskerke, 2015). Nonetheless, two-thirds of all areas will have been urbanized by 2050 (Follmann et al., 2021), though the global south is the most expected to grow faster than the rest of the world (United Nations, 2018). With this growth rate, water, food and energy supplies may be overstretched despite improved efficiencies. Models predict that most economies will experience 25-50% water scarcity by 2050 (Borgomeo et al., 2018). Inversely, waste generation is increasing and is expected to increase by 70% from its current level by 2050 (World Bank, 2018). An effect on one sector brings new changes in another sector, shifting the nexus symmetry. Several frameworks have been used to explain and establish how these processes, which are, the relationships between inputs and transitions, their outcomes and how to manage the processes and the outcomes as well. The frameworks comprise Life Cycle Analysis (LCA), Industrial Ecology, Waste Audits, Circular Economy (CE), Integrated Solid Waste Management (ISWM) and WEFW nexus.

The LCA, Waste Audit and Industrial Ecology have been applied in pollution studies, control and management. LCA is a cradle-to-grave model that analyzes individual elements from the raw material, wastes from its use and other resource use (such as energy consumption) in its life cycle. It provides credible data for policymakers to identify and quantify the specific stage of a process to intervene

and the connections between elements. It has been challenged as an expensive approach and requires deep knowledge and value judgment to make an inference (Gregory et al., 2009). Industrial Ecology examines uses and wastes from specified materials while the Waste Audit tool analyzes the flow rates and composition of materials that could be source pollutants. WEFW nexus is a quartette model based on the doctrine that a policy, strategy or initiative is likely to fail if implemented alone while undermining the others. Conversely, the success rate could be high if integration between the WEFW systems is amplified.

The focus of ISWM and CE models is the participatory processes. CE model calls for value for materials in production systems by closing loops (Richter et al., 2022) and ISWM advocates for partnerships to 'close and slow loops' in production systems. These models are built on the doctrine of mutuality and inextricability, which is also founding the CA Theory. The cells in a 'self-acting' state in the CA Theory hypothetically represent the different institutions, policies, regulations, programmes and people that enable the functioning of the WEFW sectors. Institutions work in mutuality, complementing and reinforcing each other while pooling resources in order to effectively deliver on their mandates. The action started on cell 1 (Sector 1) creates an effect in the neighbouring cell 2 (Sector 2), which transmits it to next cell 3 (Sector 3). Nature-based Solution (NbS) is an exemplary manifestation of how action on subsystem support and complements other subsystems in an ecosystem. For instance, a green-roof infrastructure, an initiative of this kind micro-regulates climate during summer but lower the pace of rain torrents which would have escalated the impacts of flash floods during rainy spell; controlled flash floods reduces the movement of sludge and leachates that are potential human and environmental health concerns and water reservoirs store water to be used in dry spell; green roofs enrich biodiversity which attracts pollinators and afterwards elevates food security.

## II. WETW NEXUS AND AUTOMATA EFFECT

Despite the wide understanding and its application, WETW nexus do not have one definition and scholars' definitions are founded on their perspectives (Dalla Longa & van der Zwaan, 2017). WEFW nexus was introduced in 2011 at Bonn during '*The Water Energy and Food Security Nexus-Solutions for the Green Economy*' conference. The focus was to accelerate integration from below the pyramid, utilization of resources and investing in sustainable ecosystem functions (Rio20, 2011). This was after it was observed that lack of integration was the major challenge with MDGs (Dalla Fontana et al., 2020). It also resonates with the knowledge that there is a robust interlink between the ecological sub-system with other city systems. This justifies the suggestion that global challenges such as climate change, urbanization and globalization should be addressed in a multisectoral approach (Stockholm Environment Institute, 2011). Similarly, the energy and materials circulation are particularly reliant on the ecosystem services of urban form and landscape. They cannot be dissociated from the highlighted challenges.

The use of WEFW differs in regions and sectors depending on the temporal scope of the goals (Endo et al., 2017). In Brazil and other Central and South American states (Ecuador, Bolivia, Chile), the application of nexus has improved energy, water and food sectors and efficient use of resources which also promotes the attainment of UNSDGs 2, 6, 7 and 13 (FAO, 2022). The success was backed up by institutional arrangements through securitization (Bazilian et al., 2011), denoting institutional capacity is among precursors both in the Global North and the South to fully implement the WEFW nexus. The argument against the application of nexus in Brazil is the skewness of studies on modelling, efficiency, technology and innovation with fewer social aspects (Dalla Fontana et al., 2020). The argument postulates that this influence the success or failure of interventions (Green et al., 2017).

While WEF research has widened since 2013 in the African context, there is a shift in conceptual and intellectual structures that have elevated new topics that have nexus perspectives (Botai et al., 2021). Some of them, counting environmental sustainability, sustainable development, climate variability and modelling, have escalated the idea of nexus from the international private corporates to local agents. A project '*Improving security and climate resilience in a fragile context through the Water-Energy-Food Security Nexus*' implemented in 3 Sahelian countries (Niger, Chad and Mali) uses a nexus approach. Its implementation began with a comprehensive evaluation of the 'often-assumed links' between natural resources, the effects of climate change, and the conflicts in the region, and address all the challenges concurrently (Nexus, 2022). The project continuity fostered new opportunities that emerge from EFW nexus and knowledge sharing. Climate change in these Sahelian countries is expected to bring in more climate variability, which interferes with rainfall patterns, causing drought and food insecurity (Niang et al., 2016). Drought also lowers water levels, which subsequently reduce hydroelectricity generation followed by power outages, energy insecurity and food spoilage in refrigerators.

Kenya is another Sub-Saharan country with the potential to tap WEFW nexus more so from the geothermal, waste, water and agriculture interlink. Regardless of being the leader in clean-green geothermal energy, the country intends to develop oil reserves projected to deliver considerable revenues to the government, for instance, 2.86% of GDP in 2015 (Wakeford, 2017). If Kenya exploits existing reserves, it would reduce the cost of exporting refined oil. The exploitation of oil resources however comes with externalities that harm the environment, society and economy (Davis, 2008; Michel & Fingas, 2016; Rocca & Viberti, 2013). Besides being the key source of GHGs, oil resource development require other resources. Its production requires about 10 litres of water/GJ of energy (Stockholm Environment Institute, 2011), yet water supply is on a decline and several families rely on vendors (Ochungo et al., 2019). The country still faces acute vulnerability to climatic changes given the large dependence on rain-fed agriculture (Wakeford, 2017). Climate change, water, food security and energy vulnerabilities are the key drivers to adopting nexus models in Kenya.

Energy poverty is equally a disregarding factor towards the security of the nexus: it is a reason for the use of wood fuel as a source of energy both at the household level and in industries (Njiru & Letema, 2018). This is not the only source of GHGs in the country. The other key sources are energy and power from residential homes that have shot projections from 7 MtCO2e in 2010 to 50 MtCO2e in 2030 (Dalla Longa & van der Zwaan, 2017). But with the country's potential to withdraw GHGs through green energy sources (geothermal, wind, solar), it pulls down projected abatement to 14 MtCO2e in 2030 (Government of Kenya, 2013). Figure 1 shows various sources of GHGs. Besides topping the list of GHGs emissions, Agriculture-related activities like transport, processing and distribution contribute to the gases.

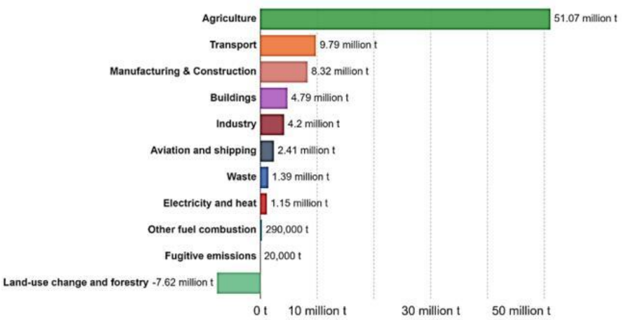


*Fig.1: GHGs emissions per sector in Kenya, Source: Our World Data, 2020*

Mitigation of GHGs thus requires multisectoral support and commitment from stakeholders to close the many emission points. This may comprise reducing the distance to transit food products to reduce transport emissions, using energy-efficient building materials to reduce emissions from buildings, electricity and heat, fuel and fugitive sources and adopting green energy technologies like solar, tidal, hydroelectric power, wind and geothermal which are readily available in these regions.

Adoption of these technologies additionally solves some other problems (like hydroelectric power solving water shortage, unemployment, food insecurity, and water resources conflicts among others, a case) which are widespread in the region. The Kurdistan dams, for example, support the agricultural sector through the water supply, energy by HEP and at the same time sustainable flood control which would have caused serious property damage, fears and food insecurity in the Kurdistan Province (Azizi, 2018). Significant waste issues are however not well documented in this project, though flood control has an impact on sludge and leachate flow. A properly-coated landfill which is devoid of absorbency shields against contamination of aquifers, which afterwards safeguards human and other ecological entities from consuming polluted water. Overlooking this association by using a single perspective for a complex wicked problem is a reason some solutions are costly and skewed. Instead, solutions should tap piggyback benefits from a single solution, supposedly, an NbS.

Overall, the adoption of green technology created ambitions of significantly reducing GHGs and was projected to lower fossil fuel reliance (Dalla Longa & van der Zwaan, 2017). This lessens the triggers of climate change and global warming and avoids consequences that would otherwise destroy economic assets and revenues that indirectly serve the people. A Hydro Electric Power project in Kisii (Kenya) is an example of this interdependency: studies found a decline in power bills by 79% once the project is operationalized (Kitio, 2014), as well as the use of wood and fossil fuel. Another example is Homa Bay town which confronts persistent water shortages due to high electricity costs (Ongeko et al., 2017) which also translates into a low revenue base (Kitio, 2014). The water-energy nexus effect is similarly observed in Kisumu city. The city has the potential of producing energy from wind, which is predicted to reduce the high cost of electricity and can be used to supply water for food production.

There are other countries in the Global South that are now substituting fossil-driven machinery to mitigate the adverse effects of GHGs. In Rwanda, the focus is on reducing dependency on oil and chemical fertilizers to reduce its carbon footprint (GoR, 2011). The country has also constructed a biogas plant in Kigali prison to cut the

biomass energy demand by 70% and uses the effluent for food production (Kitio, 2014). Water stress is another global problem that is connected to other elements in an urban setting. The water vending trade is not unusual. By 2050, almost half the population will have to rely on food imports unless crop production adjustments are made (Stockholm Environment Institute, 2011). These are mostly in poor countries facing water scarcity. The water-stress problem spills over to food insecurity: water scarcity is expected to reduce food production by over 65% of the current levels in Saudi Arabia, Yemen (35%) and SAR (18%) (Borgomeo et al., 2018). This has a bearing on the economy of a country (Figure 2).

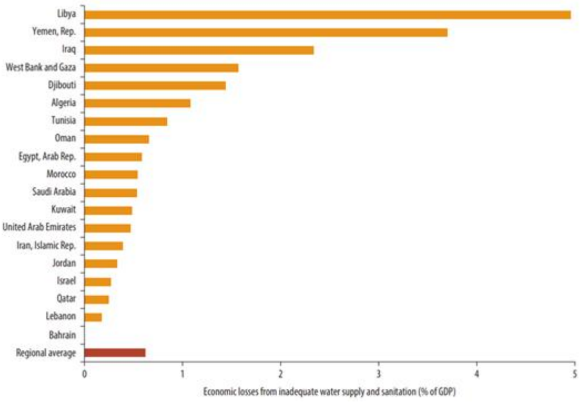


*Fig.2 Estimated agricultural exports in the ME and N. Africa, Source: World Bank 2018*

Despite its complexity and challenges in its implementation, nexus presents opportunities for more comprehensive policy solutions to address the nexus problems (FAO, 2022). Avoiding trade-offs while generating benefits that outweigh the cost associated with integration is a co-benefiting characteristic of the WEFW nexus. The benefits are designed in a manner that attracts interest from the private sector, the government and civil society groups and reduce intersectoral trade-offs and externalities (Petrariu et al., 2021).

Kenya's Vision 2030 specifies how to manage waste, LULUCF mapping, and reduce wood and petroleum usage in the transport and manufacturing sector (Government of Kenya, 2007). The Vision 2030 envisages the construction of water projects comprising multipurpose dams in River Nzoia and Nyando, the Tana Delta project and the rehabilitation of many river basins with the view of supplying clean water to communities (Government of Kenya, 2007). The multifunctionality illustrates tapped piggybacks on a nexus platform.

## III. CHALLENGES WITH THE NEXUS

Poor linking of the nexus elements is another common practice more so the waste and biodiversity elements, leading to ecological disasters like subjecting species to the endangered list (Gómez-Camacho et al., 2020). This is pronounced in how waste is not considered a big problem and is easily discarded through open dumping and burning in the Global South regardless of unintended socio-ecological consequences. Similarly, LULUCF is taken as a solution to agricultural land inadequacy but is a short-term solution and a huge threat to endangered and threatened species. Energy development and usage have also created negative effects that are either wasteful or environmentally degrading (Andrews-Speed & Zhang, 2019). These fears and uncertainties explain the incomplete integrations of all nexus elements in development programmes. Integrating environmental priorities into sustainable development policies, for example, is a challenge for developing countries that are still struggling with socioeconomic challenges such as inequality and social injustice (Dalla Fontana et al., 2020). There is also an incongruity in knowledge, that the high frequency of the nexus knowledge emerges from the Global North but is largely applied in the Global South, mostly South East Asia (Wiegleb & Bruns, 2018). Trading off these elements against each other is also common. The waste aspect is mostly traded off in the WEFW equation (Dalla Fontana et al., 2020; Gulati et al., 2013; Guo et al., 2020; Wicaksono & Kang, 2019) or completely left out because it is seen as insignificant (Gómez-Camacho et al., 2020).

## CONCLUSION

The crucial role played by nexus in urban sustainability cannot be disregarded. Understanding how nexus operates, enablers and changes in state help to project scenarios and improve the decision-making process in developing comprehensive and integrated strategies for the next generation. In this regard, the application of Automata Theory on the nexus model, particularly the change in state and how it affects other elements of the WEFW nexus such as how impacts of climate change on water affect food and how it transfers the effect to energy and then to waste generation, and subsequent systematic permutations of each of these elements against each other, must be studied in detail. This could shed light on the key interventions that urban managers can use to tighten the sustainability loopholes in the Global South cities.

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